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Design and parametric analysis of Linear Joule-cycle Engine with out-of-cylinder combustion

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Abstract

For all the existing prime movers including internal combustion engine and gas turbine, there is an inherent problem as the efficiency penalty in their micro scale applications. Crankshaft mechanism in internal combustion engine causes nearly half of the friction loss originating in piston-ring-cylinder contacts. Rotomachinery of compressor and turbine results in low compression and expansion efficiencies when gas turbine downsizes to couple kilowatts. Linear Joule-cycle Engine (LJE) is designed to hire Joule cycle and out-of-cylinder combustion, to configure a double-acting free piston setup without crankshaft mechanism. The paper introduces the innovative design of LJE and optimises its geometry parameters in LMS Imagine.Lab AMESim. The parametric analysis provides a solid basis to prototype manufacturing. The potential of the technology lies on micro energy supplies using various renewables.

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Keywords: Linear Joule-cycle Engine; free piston; parametric analysis; prototype design

1. Introduction

The very first reciprocating Joule-cycle engine concept can date back to 1807, when a British, Sir George Cayley, brought a new concept engine with separate expander and compressor working on Joule cycle or Brayton cycle. This heat engine concept has been revived since the beginning of the 21th century largely due to its potential of high efficiency and adaptability to renewable energy. In 2003, another British, Bell [1] picked up the design with a traditional crank shaft engine. He introduced a first-order model of a reciprocating Joule-cycle engine and investigated the effects of regenerative heat exchange, friction, combustion, clearance volume, leakage and pressure drops. It is shown that a thermal efficiency of 50% might be achievable under realistic conditions using a maximum operating temperature of 1300 K while the pressure ratio is in the range of 6-8. In 2005, Moss, Roskilly and Nanda [2] continued to explore the potential of a reciprocating Joule-cycle engine for a small size domestic CHP application (1-10 kW).

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They predicted that a 5 kW Joule-cycle engine with pressure ratio of 7.5 has an overall electrical efficiency of 33.2%. Alaphilippe, Bonnet and Stouffs [3] did a theoretical investigation on the coupling of a two-stage parabolic trough concentrator with a reciprocating hot-air engine in 2007. Also applying reciprocating engine, with external heating, in 2010, Wojewoda and Kazimierski [4] introduced a dynamic engine model based on a closed Joule cycle with crankshaft mechanism. They were looking into relatively big system larger than 30 kW output and a potential application on future ships which has artificial sails and uses solar externally heating reciprocating Joule-cycle engine as backup. The efficiency of their engine is predicted about 25-30% driven by 800-1000°C solar thermal energy external heating. Mikalsen and Roskilly [5] raised a new concept design of free piston Joule-cycle engine. In a theoretical calculation, the working conditions were 800°C of heating temperature, 6 bar of compressor outlet pressure. The engine produced 4.5 kW of mechanical power with 32% efficiency. More recently, Creyx, et al. [6] conducted a study on a static model for Joule or Ericsson cycle engine (crankshaft mechanism) with external heating and applied the model onto previous cases in the literatures. It concluded the optimised parameters for such engine, including a highest pressure of 6 bar, heating temperature of 650°C and rotation speed of 600 rpm. With the optimal parameters, the engine generates 795 W power output with 37.6% efficiency.

As for Joule-cycle engine, free piston setup has its advantage in comparison of reciprocating crankshaft mechanism, since less friction, less mechanical efficiency loss and much more compactness. In this paper, the authors present a design of Linear Joule-cycle Engine prototype with free piston setup and linear induction alternator. Direct out-of-cylinder combustor or heater and open cycle are applied to configure a heat engine. A parametric analysis is conducted to optimise the geometry design of the LJE.

2. Design of Linear Joule-cycle Engine

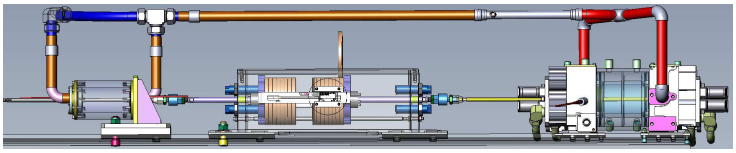

Fig 1. 3D design diagram of the Linear Joule-cycle Engine prototype

The LJE design is shown in Fig 1. The components are compressor, expander, heater (combustor) and damping force generating device (moving mass case in the middle) which simulates a linear induction alternator. Two double-acting free pistons are placed in the compressor (left end) and the expander (right side) respectively, which separate cylinders into two opposite chambers. A rigid piston rod connects two pistons, and the moving mass plates on the rod acting as the translator of linear alternator. The out-of-cylinder combustor/heater is placed between the compressor and the expander and connected them with pipes. On the compressor and expander, there are intake valves and exhaust valves at both ends to intake and expel working fluid - air. Control algorithm is deployed in the Labview control system to decide the opening and closure timing of the valves in terms of measured real-time parameters, including piston displacement, working air pressure and temperature.

The theoretic thermodynamic cycle applied in LJE consists of four processes, as shown in Fig 2. A-B is the adiabatic reversible compression, when air is drawn into and compressed in the compressor. B-C is the constant pressure fuel combustion - idealised as constant pressure heat addition, when fuel is mixed with the high pressure air and burned at constant pressure. C-D is

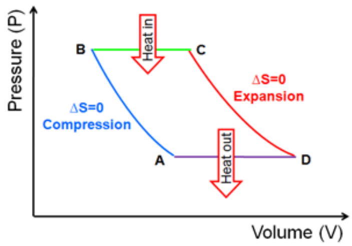

Fig 2. Ideal Joule cycle

the adiabatic reversible expansion, when hot and high pressure gases enter two opposite expander chambers and expand in the chambers alternatively, to push the piston conducting linear motion back and forth. The mechanical power from the linear motion is partly to drive the compressor piston for the compression process, and the remaining power is the output to drive a linear generator for electricity generation. D-A is the constant pressure exhaust process, which is the constant pressure ejection of the spent, hot gases to the environment.

3. Parametric analysis results and discussions

The dynamic model of LJE was constructed in AMESim, where thermodynamic, mechanical and control systems of the prototype have been integrated into one systematic model. Due to the periodical open and closing of intake and exhaust valves, the chambers of the expander and the compressor are set as control volumes respectively, where the working fluids flow through them dynamically. The friction forces posed onto the pistons and the moving mass in motion include viscous friction force and Coulomb friction force. Windage force is also considered as one of the resistant forces. Apart from these, the slight leakage from one chamber to the opposite chamber also causes very small viscous friction affection, which is added onto the dynamic balance of the piston-rod in motion. Similar to the compressor and the expander models, the combustion chamber is modeled as a control volume with dynamic flows. In the LJE model, some geometry parameters strongly affecting the engine performance are investigated, for instance cylinder length and diameters, piston stroke, piston-rod weight, etc.

Table 1. Impacts on engine performance by different cylinder lengths and target strokes

Cylinder length (mm)	Target stroke (mm)	Heating power in (kW)	Mechanical power output (kW)	Highest pressure (bar)	Frequency (Hz)	Efficiency (%)
80	76	8.74	2.59	3.9	33.8	29.6
120	116	13.9	4.47	5.9	36.4	32.2
160	156	18.34	5.41	7.8	37	29.5

The LJE works at a maximum temperature of 800°C. The intake air pressure and temperature are ambient. If the moving part, the piston-rod (including the moving mass), has a total weight of 1 kg, and the diameters of compressor and expander are known, the stroke and cylinder length become the variables to be optimised. The impacts of different stroke and cylinder length on output parameters have been presented in Table 1. With a fixed diameter of compressor cylinder, the longer stroke indicates that the piston swaps a longer distance before the end of compression process; in turn a greater compression ratio can be achieved. Since the piston-rod weight is a constant, a greater maximum pressure posed on the expander piston leads to a faster acceleration and a greater maximum velocity of the piston before the exhaust valves close and an air cushion has been formed for deceleration of the piston-rod. Apart from the greater maximum pressure, the longer cylinder length also increases total volume of air intake. Therefore, the flow rate of the working air throughout the system increases, which demands more heating power to maintain a maximum temperature of 800°C. A long stroke has the adverse impact as well, which is more friction during the course and other problems as linearity of the rod and air tightness at the rod bearing, etc. In Table 1, it is shown that an optimal stroke and cylinder length can be concluded in terms of the maximum engine thermal efficiency. The optimal efficiency of 32.2% can be reached when the cylinder length is 120 mm and the target stroke is 116 mm.

In Table 2, the major output parameters are listed according to the variation of compressor diameter and volume ratio (expander volume to compressor volume). In the comparison, the cylinder length and stroke are set as 120 mm and 116 mm from the optimal parameters above. If the expander diameter is remained the same, with the increase of compressor diameter from 52 mm to 73 mm, the volume ratio drops. However, the bigger volume ratio doesn't guarantee the better performance. Due to the mass balance of the air flow, bigger volume ratio results in lower maximum pressure, which causes slower linear motion, lower frequency and less net power output eventually. But if the volume ratio is getting too small, more power generated from the expander is consumed in the compression process, which leads to smaller fraction of net power output and lower efficiency. The optimal volume ratio is established around 1.5 for this particular engine setup.

Table 2. Impacts from the diameter of compressor cylinder and volume ratio between compressor and expander

Compressor diameter (mm)	Volume ratio	Heating power in (kW)	Mechanical power output (kW)	Highest pressure (bar)	Frequency (Hz)	Efficiency (%)
52	2.37	6.94	2.06	3.9	25.1	29.7
66	1.47	13.9	4.47	5.9	36.4	32.2
73	1.20	17.94	5.11	6.8	42.7	28.5

In practice, the translator weight (the moving mass in the LJE design, as a part of the piston-rod moving part) of linear induction alternator is an influential variable to the engine design. In Fig 3, the correlation of the piston-rod mass with engine frequency and efficiency is presented. Heavier moving mass would always cause smaller acceleration, lower maximum velocity, and finally slower frequency. For the impact on efficiency, heavier moving mass can lead to dramatically shift of efficiency at first, because the fast dropping frequency results in less distance covered by the pistons, and less friction generated consequently. But with the change of frequency getting slowly, the impact of heavier mass and larger friction forces would overweight the other factors. The efficiency starts to decrease gradually after the moving mass weighs over 2 kg as the optimal geometry parameter.

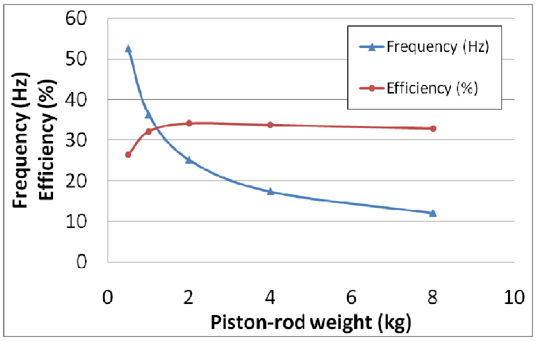

Fig 3. Piston-rod mass versus frequency and efficiency

4. Conclusions

In micro scale, LJE provides a high efficient alternative for mechanic power or electricity generation. The design of a LJE prototype demonstrates its simplicity and compactness. The parametric analysis reveals the inherent correlations between variables, such as cylinder length, stroke, diameter, piston mass, and engine performance parameters, for an optimal design and viable prototype.

References

[1] Bell M.A., Partridge T. Thermodynamic design of a reciprocating Joule Cycle engine. In: Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy pp.217-239, 2003.

[2] Moss R.W., Roskilly A.P., Nanda S.K. Reciprocating Joule-cycle engine for domestic CHP systems. In: Applied Energy Vol.80, pp.169-185, 2005.

[3]Alaphilippe M., Bonnet S., Stouffs P. Low power thermodynamic solar energy conversion: Coupling of a parabolic trough concentrator and an Ericsson engine. In: International Journal of Thermodynamics Vol.10 (No. 1), pp.37-45, 2007.

[4] Wojewoda J., Kazimierski Z. Numerical model and investigations of the externally heated valve Joule engine. In: Energy Vol.35, pp.2099-2108, 2010.

[5] Mikalsen R., Roskilly A.P. The free-piston reciprocating Joule Cycle engine: A new approach to efficient domestic CHP generation. In: Proceeding of ICAE2012 Conference, 2012.

[6] Creyx M., Delacourt E., Morin C., Desmet B., Peultier P. Energetic optimization of the performances of a hot air engine for micro-CHP systems working with a Joule or an Ericsson cycle. In: Energy Vol.49, pp.229-239, 2013.